

Semi-Autonomous Scheme for Pushing Micro-Objects

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Abstract—In many microassembly applications, it is often desirable to position and orient polygonal micro-objects lying on a planar surface. Pushing micro-objects using point contact provides more flexibility and less complexity compared to pick and place operation. Due to the fact that in micro-world surface forces are much more dominant than inertial forces and these forces are distributed unevenly, pushing through the center of mass of the micro-object will not yield a pure translational motion. In order to translate a micro-object, the line of pushing should pass through the center of friction. In this paper, a semi-autonomous scheme based on hybrid vision/force feedback is proposed to push microobjects with human assistance using a custom built tele-micromanipulation setup to achieve pure translational motion. The pushing operation is divided into two concurrent processes: In one process human operator who acts as an impedance controller alters the velocity of the pusher while in contact with the micro-object through scaled bilateral teleoperation with force feedback. In the other process, the desired line of pushing for the micro-object is determined continuously using visual feedback procedures so that it always passes through the varying center of friction. Experimental results are demonstrated to prove nano-Newton range force sensing, scaled bilateral teleoperation with force feedback and pushing microobjects.

I. INTRODUCTION

As the nature has provided us with things in a dimension ranging down till micro/ nanometers likewise humans also were able to fabricate components in the same scales, but the prominent challenge lies in the fact to assemble incompatible components in a single and functionalized product or micro/nano systems. Complex micro/nano systems in general contain much distinct functionality in a single product and comprise of different types of materials. Use of monolithic ways to produce complex micro/nano systems is desirable, but unfortunately is not always feasible. The current state of art is to incorporate components into a single functional product and to assemble simple parts one by one [1], [2], [3]. The only solution to this problem is develop microassembly setup capable to assembly micro-parts using human assistance. The first and foremost requirement for the assembly process is to “precisely manipulate” objects. Manipulation includes cutting, pushing, pulling, indenting, or any type of interaction which changes the relative position and relation of entities. This paper concentrates on manipulation by pushing as it is a useful technique for manipulating delicate, small, or slippery parts, parts with uncertain location, or parts that are otherwise difficult to grasp and carry [4], [5], [6]. The process of manipulation by pushing of micro-objects possesses many challenges due to the requirements of:

- Actuators with high resolution (in nanometer range), high bandwidth (up to several kilo hertz), large force output (up to few tons) and relatively large travel range (up to a few millimeters) [7].
- Robust and transparent bilateral controllers for human intervention so that high fidelity position/force interaction between the operator and the remote micro environment can be achieved [8], [9].
- Vision based algorithms to estimate the location of objects being manipulated and visual servoing to position manipulators so that these objects can be pushed along a desired trajectory [10].
- Controlled pushing force to generate the desired pushing forces compensating surface forces arising between the object and the environment.

Manipulating objects with high dexterity requires not only precise position control of actuators but also delicate control of forces involved in the manipulation process. Visual information is required for path planning whereas use of force feedback is indispensable to ensure controlled physical interactions. Thus, pushing using only visual feedback is not sufficient but it is also indispensable to sense and control the interaction forces involved in the manipulation process with nano-newton resolution, in other words to adopt vision/force hybrid feedback method for force controlled pushing. In this paper, a semi-autonomous scheme for pushing micro-objects using hybrid vision/force feedback method is utilized.

The paper is organized as follows. Section II provides the problem definition and approach and Section III explains the custom built tele-micromanipulation setup. In Section IV, scaled bilateral teleoperation is demonstrated with experimental details concerning force/position tracking between the master and the slave. Finally, Section V provides the procedure for pushing micro-objects along with the experimental results and Section VI concludes the paper and discusses future directions.

II. PROBLEM DEFINITION AND APPROACH

The problem dealt within this work concerns utilizing semi-autonomous manipulation scheme for pushing of polygonal micro-object, by point contact to achieve pure translational motion with the aid of a human operator employing scaled bilateral teleoperation with force-feedback and visual display. In order to achieve pure translation motion, the proper line of action of the pushing force needs to always pass through the

varying center of friction of the polygonal micro-objects. Thus, while the pushing operation is in progress, it is inevitable to online estimate the center of friction and align the probe such that line of action passes through the center of friction of the micro-object.

The above mentioned problem is coped with by utilizing a proposed method for pushing polygonal micro objects using semi-autonomous scheme with human assistance as shown in Figure 1. The whole process of pushing a micro-object is divided into two concurrent process: in one process pushing is performed by the human operator which acts as an impedance controller to switch between force-position control and alters the velocity of the pusher while in contact with the micro-object. In the second part, the desired line of pushing for the micro-object is determined continuously so that it always passes through the varying center of friction.

Human operator utilizes the scaled bilateral control structure as demonstrated in Section IV to generate the desired position which is scaled with a factor α before feeding to the position controller. The position controller uses the feedback from PZT actuator to compensate the position error to achieve the desired position of the piezoresistive micro-cantilever. As the micro-cantilever comes in contact with the micro-object the interaction resultant forces are felt by the human operator through the force fed from the piezoresistive micro-cantilever after scaling by a factor of β . Depending upon the situation human operator which acts an impedance controller can adjust the impedance (effective muscle stiffness) to change from position control to force control to push that micro-object along X-axes with the commanded position/force. Moreover, the operator has the access to the visual information for monitoring the pushing process. Visual feedback procedures is performed automatically to estimate the correct line of pushing to achieve pure translational motion. Visual processing algorithms are employed to detect position and orientation of the micro-object for the estimation of the location of the center of friction. Finally, the velocity of the piezoresistive cantilever is varied at the contact point using visual feedback process to ensure that resultant line of pushing passes through the center of friction to achieve pure translation motion along the X-axes.

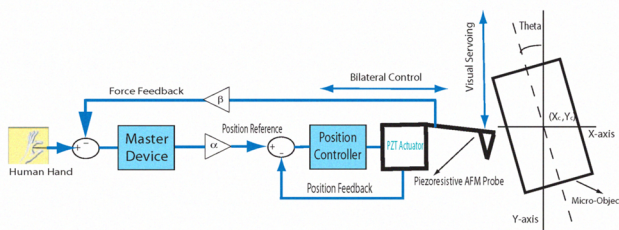


Fig. 1. Hybrid control structure for semi-automated pushing

III. MICROMANIPULATION SETUP

The system is composed of two parts, namely a master mechanism operated by the human operator and a slave mechanism interacting with the micro environment. For the master

mechanism a DC motor is utilized, while a piezoresistive microprobe attached on PZT stacks is used for the slave. A bilateral man-machine interface is implemented for control as shown in schematics Figure 1.

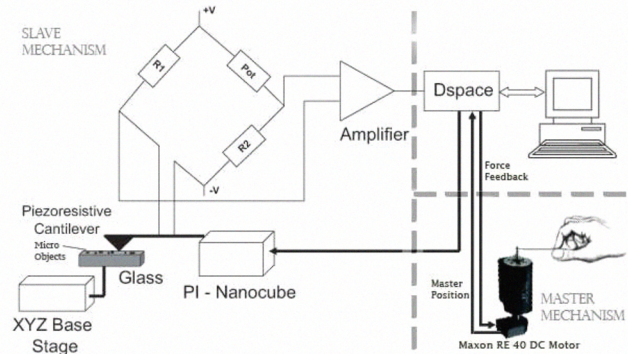


Fig. 2. Schematic of tele-micromanipulation system.

The position data from the master side is scaled and transferred to slave side, while simultaneously, the force measured at the slave side is scaled and transferred back to master. XYZ base stages are manually operated PZT which are used for proper alignment of micro object or in other words to bring the micro objects under the workspace. A graphical display is also made available to the operator through the signal processing card where the bilateral control algorithms are implemented. Figure 2 shows the experimental setup. The one degree of freedom master mechanism consists of a brushed DC servo (Maxon motors RE40) and is manually excited with the help of a light rod that is connected to the shaft. The slave mechanism includes different components to ensure reliable and efficient micromanipulation. Capability to control positions with nanometer accuracy and to estimate the forces in nano-Newton scales is required. High magnification microscopy is also essential for visual feedback with acceptable resolution.

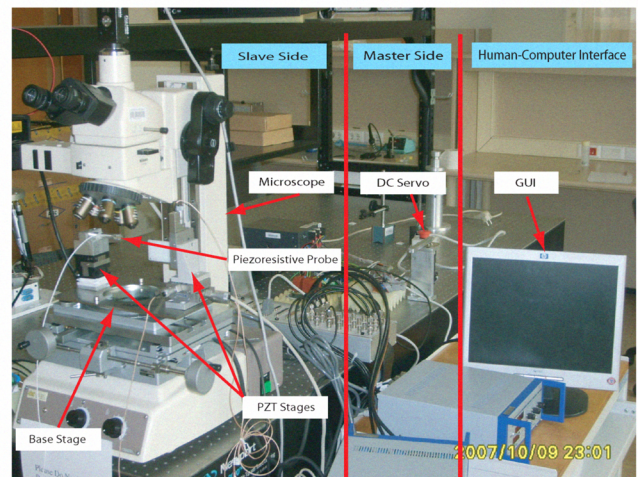


Fig. 3. Experimental setup for micromanipulation

An open architecture micromanipulation system that satisfies the requirements has been developed and used as the slave

mechanism. Nano scale positioning of the micro cantilever has been provided using three axes piezo stages (P-611 by Physik Instrumente) which are driven by a power amplifier (E-664) in closed loop external control mode. Potentiometers (strain gauge sensors) integrated in the amplifier, are utilized for position measurement of the closed loop stages which possess a travel range of $100\text{ }\mu\text{m}$ per axis with one nanometer theoretical resolution. Stictionless and frictionless compliant guiding systems exist in the stages. An open loop piezoelectric micrometer drive (PiezoMike PI-854 from Physik Instrumente) has been utilized as the base stage, which is equipped with integrated high resolution piezo linear drives [10]. Manually operable linear drives are capable of $1\text{ }\mu\text{m}$ resolution and the automatic movement range of the micrometer tip with respect to the position can be set $50\text{ }\mu\text{m}$ ($25\text{ }\mu\text{m}$ in/out). Nanometer range resolution is achieved for this movement by controlling the piezo voltage. As for the force feedback, a piezoresistive AFM cantilever (from AppNano) has been utilized along with a inbuilt Wheatstone bridge. A real time capable control card (dSPACE DS1103) is used as control platform and an optical microscope (Nikon MM-40) is used for visual feedback.

IV. SCALED BILATERAL TELEOPERATION

In this section implementation of scaled bilateral control in a custom built tele-micromanipulation setup is presented. Force sensing with nN resolution using piezoresistive AFM (Atomic Force Microscope) micro-cantilever is demonstrated. Force/position tracking and transparency between the master and the slave is presented with varying references after necessary scaling.

A. Force Sensing Using Piezoresistive AFM Microcantilever

In order to achieve force transparency between master and slave, its necessary to sense the force in nano-newton range with high accuracy. Piezoresistive AFM cantilever with inbuilt Wheatstone bridge from AppliedNanostructures is utilized as a force sensor as well as probe for pushing operation as shown in Figure 5.1. Piezoresistive sensors have been used for many other MEMS applications, including accelerometers, gyroscopes and AFM cantilevers. The primary advantage of this approach is that the sensor impedance is relatively low (a few $K\Omega$), and it is possible to extract small signals without interference from noise with off-chip integrated circuits.

The working principle is based on the fact that as the force is applied at the free end of the cantilever using the PZT actuator with the glass slide, the change of resistance takes place depending on deflection of the cantilever. The amount of deflection is measured by the inbuilt Wheatstone bridge providing a voltage output, which is amplified by the custom built amplifier. To match with the initial cantilever resistance value, one of the active resistors in the full bridge is replaced by a potentiometer. The amplified voltage is send to the data acquisition dSpace1103 card for further processing.

1) Experimental Results for Force Sensing:

Figure 5 [11], [12] represents the attractive forces for pulling in phase between the tip and glass slide. The

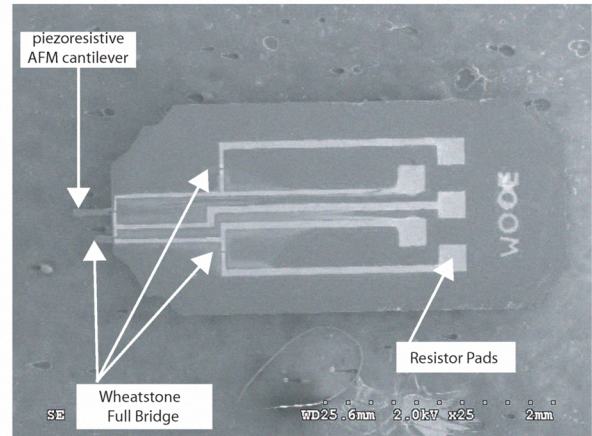


Fig. 4. Piezoresistive AFM Cantilever with inbuilt Wheatstone bridge

decreasing distance between the tip and glass slides is represented by the increase in the position of PZT axis. As the distance between the tip and glass slide decreases the attractive forces increases. The result clearly indicates that force sensing with the resolution of nN range is achieved.

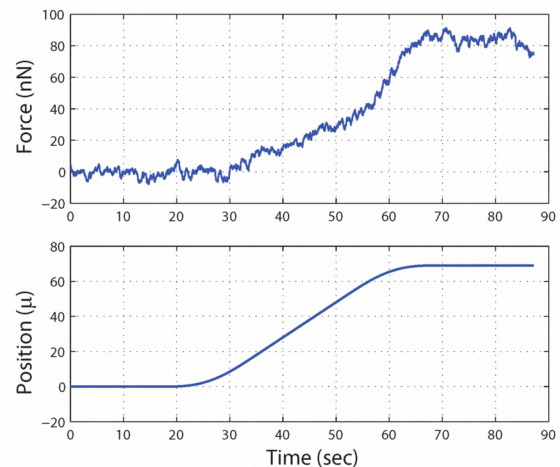


Fig. 5. Force for smooth step position reference.

B. Scaled Bilateral Control Structure

In the micromanipulation applications, scaled bilateral control is used for teleoperation where master/human is not able to access the micro environment on the slave side. Since the master and slave are working on macro and micro scales respectively, thus its indispensable to use general bilateral controller to scale the position and forces between two sides for extensive capability [13]. In other words, position information from the master is scaled down to slave and force information from the slave side is scaled up to master as shown in Figure 6 comprising of master and slave side. Piezo-stage on the slave side is required to track master's position as dictated by position controller. The 1D force of interaction with environment, generated by piezoresistive cantilever, on

the slave side is transferred to the master as a force opposing its motion, therefore causing a “feeling” of the environment by the operator. The conformity of this feeling with the real forces is called the “transparency”. Transparency is crucial for micro/nanomanipulation application for stability of the overall system. Furthermore, for micro system applications, position and forces should be scaled in order to adjust to operator requirements. Position of the master manipulator, scaled by a factor α , is used as a position reference for the slave manipulator, while the calculated force due to contact with environment, scaled by a factor β , is fed-back to the operator through the master manipulator.

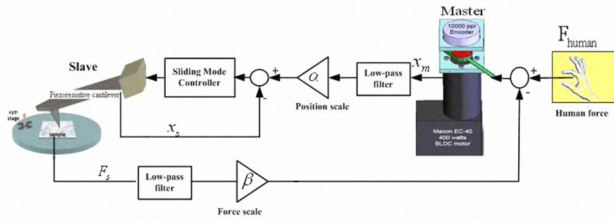


Fig. 6. Scaled bilateral teleoperation control structure

In order to eliminate oscillations both on master side because of oscillatory human hand and on the slave side due to piezoresistive cantilever dynamics, position of master manipulator and force of slave manipulator are filtered by low pass filters before scaling.

1) *Scaling of the Position and Force Information:* Since the master and slave side resides on macro and micro scales respectively, thus its very vital to appropriately choose the scaling factor in order to attain the optimum performance. In the ideal condition, the steady state condition of the bilateral controller should be Eqn.(1).

$$\begin{aligned} x_s &= \alpha x_m \\ F_m &= \beta F_s \end{aligned} \quad (1)$$

Where α and β represents the position and force scaling respectively. x_m, x_s denotes the master and slave position respectively and F_m, F_s denotes the master and slave force respectively. To be able to meaningfully interact with the micro environment, positions and forces are scaled to match the operator requirements.

In the first and second experiments, scaling factors of $\alpha = 0.027 \frac{\mu m}{deg}$ and $\beta = 0.00366 \frac{N}{nN}$ are used, that is an angular displacement of $1deg$ on the master side corresponds to a linear displacement of $1\mu m$ on the slave side and a force of $0.00366nN$ on the slave side corresponds to a force of $1N$ on the master side. The objective of these experiments is to provide very fine motion on the slave side for a relatively larger displacement on the master side, hence α is selected according to this objective. Then the corresponding forces/torques for each amount of displacement were compared for the selection of β , keeping in mind that the DC motor on the master side has low torques.

2) *Experimental Validation for Force/Position Tracking:* In order to validate the position tracking between the master and slave, the commanded position from the master is transferred after necessary scaling to be tracked by the slave side. Figure 7 illustrates the experimental results for position tracking along with the tracking error of the bilateral controller. It can be clearly seen that the slave tracks the master position with high accuracy. This position tracking performance is acceptable for precisely positioning the micro cantilever.

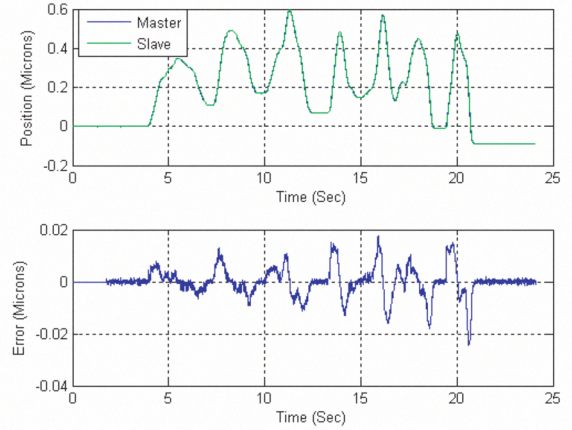


Fig. 7. Position Tracking between the master and the slave

In order to validate the force tracking, the slave forces encountered from the environment is being transferred to the master side after necessary scaling. Figure 8 demonstrates the force tracking between the master and slave along with the tracking error. It can be clearly observed that the master tracks the slave force precisely.

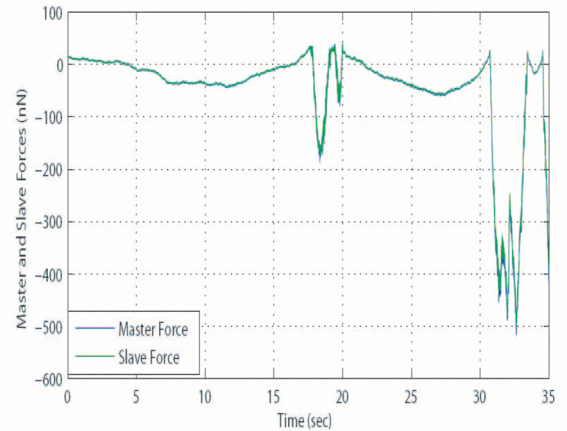


Fig. 8. Force tracking between the master and the slave

V. SEMI-AUTONOMOUS PUSHING SCHEME

A. Point Contact Pushing For Translational Motion

Precise positioning of micro-objects lying on a substrate using a point contact pushing to track a desired trajectory poses

lot of challenges. The pusher or probe needs to be controlled in such a way to reorient and transport the microobject to its final location using a stable pushing¹ operation. Using only a point contact with a limited number of freedom the task of pushing on a horizontal plane can be realized.

In this work, pure translation of a regular object from one location to another by orientating the line of action of the pushing force to the desired direction is presented. The desired translational motion of the object cannot be achieved if the line of pushing at the contact point passes through the center of the mass of the micro-object. Due to the dominance of the frictional forces existing in between the micro-object and supporting surface, the inertial effect will be neglected and the motion will be dependent upon the motion and direction of the frictional forces. Thus, the resultant line of pushing needs to be directed through the centroid of the frictional distribution, center of friction² where all the distribution of friction can be lumped into a single point to achieve pure translational motion [14]. The pushing mechanism to achieve pure translational motion is explained in detail in the following subsection. Moreover, due to uncertain topography of the surfaces the frictional distribution changes with respect to time, giving rise to the unpredictable location of the center of friction which is not constant over time. Thus, the most important task lies in the online estimation of the center of friction using visual and force information.

B. Trajectory Control for Known Center of Friction

Figure 9 represents the scenario of pushing rectangular object using a point contact pushing to achieve pure translation motion. The rectangular micro-object has two points, namely COM (center of mass) and COF (center of friction). The contact point of the pusher is taken as the origin of the reference frame. The x-axis and y-axis of the frame is chosen to be parallel and perpendicular connecting to the edge of polygon. The velocity of the probe along x-axis (\vec{V}_x) and y-axis (\vec{V}_y) are controlled by visual feedback and human operator, respectively. The desired velocity vector \vec{V}_{des} , resultant of \vec{V}_x and \vec{V}_y needs to pass through COF, hence have an angle θ_d to achieve a pure translation motion. The value of \vec{V}_y cannot be controlled to achieve the desired velocity vector as it is administered by the human operator, rather it is only a measurable quantity. The variable \vec{V}_x can be calculated by taking into consideration the value of \vec{V}_y to achieve the desired velocity vector \vec{V}_{des} making an angle θ_d as in the following equations.

The relationship between the \vec{V}_x and \vec{V}_{des} can be written as Eqn.(2) by analyzing Figure 9 and solving for \vec{V}_{des} yields Eqn.(3).

$$\vec{V}_{des} \cos \theta_d = \vec{V}_x \quad (2)$$

¹The probe or pusher is always in contact with the micro-object during the pushing operation.

²Center of friction is defined as single point where the frictional distribution between the interface of object/substrate can be lumped.

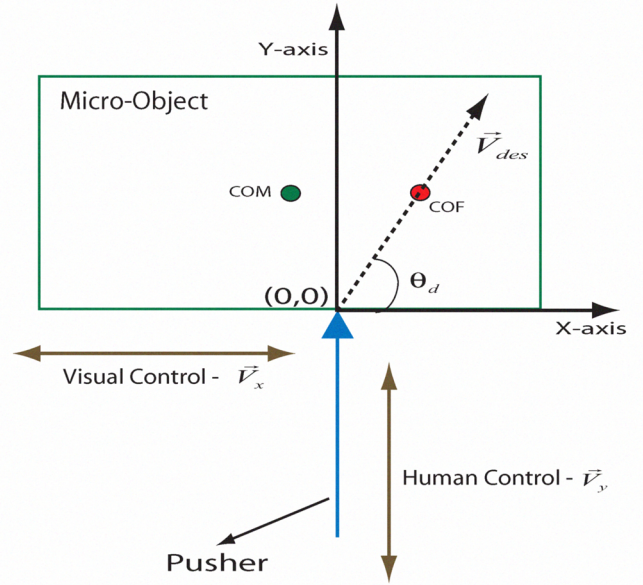


Fig. 9. Calculation of velocity vector for known center of friction

$$\vec{V}_{des} = \frac{\vec{V}_x}{\cos \theta_d} \quad (3)$$

Similarly, the relationship between the \vec{V}_y and \vec{V}_{des} can be written as Eqn.(4) and inserting the Eqn.(3) into Eqn.(4) will yield Eqn.(5)

$$\vec{V}_{des} \sin \theta_d = \vec{V}_y \quad (4)$$

$$\vec{V}_y = \vec{V}_x \tan \theta_d \quad (5)$$

The Eqn.(5) indicates that it is possible to only control \vec{V}_y to achieve the resultant velocity vector \vec{V}_{des} to pass through COF. As it is already discussed, the location of the COF is not constant with respect to time, thus it is necessary to calculate the location of COF.

C. Method for Online Estimation of the Center of Friction

As mentioned in the previous section, due to dominance of adhesion (surface) forces in the micro-world, the friction distribution between the micro-object and supporting surface alters giving rise to unpredictable changes of COF. The change in the location of the COF may be very fast due to unexpected changes in frictional distribution, thus online estimation of COF needs to be performed and the probe needs to align so that the line of action of the applied force F_c passes through the COF.

Visual information is utilized to determine the position and velocities of the four corners, the centroid of mass for the rectangular micro-object along with the position of the contact point $p_c = (x_c, y_c)$ with the probe. The instantaneous center of rotation p_r and orientation angle θ are calculated using image processing techniques. The force F_c measured by the probe is coupled and can be decomposed into two dimensions as $F_{cx} =$

$F_c \cos \theta$ and $F_{yx} = F_c \sin \theta$. The moment M_{cz} generated by the applied force be written as

$$M_{cz} = x_c F_{cy} - y_c F_{cx} \quad (6)$$

Once two consecutive visual frame are captured while pushing and Eqn.(7) represents the relationship between the pushing force F_c and frictional force vector f which can be written as

$$F_c = Gf \quad (7)$$

where F_c is calculated for each two consecutive frames captured using as

$$F_c = [sgn(\dot{\theta}_1)F_{cx1}, sgn(\dot{\theta}_1)F_{cy1}, sgn(\dot{\theta}_1)M_{cz1}, sgn(\dot{\theta}_1)F_{cx2}, sgn(\dot{\theta}_2)F_{cy2}, sgn(\dot{\theta}_2)M_{cz2}]^T \quad (8)$$

where F_{cx1} , F_{cy1} , M_{cz1} represents pushing force in x-axis for the first captured frame, pushing force in y-axis for the first captured frame and moment in the z-direction for the first captured frame respectively. Similarly F_{cx2} , F_{cy2} , M_{cz2} represents for the second captured frame. The value of $G_{4 \times 6}$ matrix is calculated using two sets of consecutive captured frame and four supporting points considering the vertices of the rectangle. The $G_{4 \times 6}$ is written as

$$G = \begin{bmatrix} \frac{-Y_{11}}{R_{11}} & \frac{-Y_{21}}{R_{21}} & \frac{-Y_{31}}{R_{31}} & \frac{-Y_{41}}{R_{41}} \\ \frac{X_{11}}{R_{11}} & \frac{X_{21}}{R_{21}} & \frac{X_{31}}{R_{31}} & \frac{X_{41}}{R_{41}} \\ \frac{x_1 X_{11} + y_1 Y_{11}}{R_{11}} & \frac{x_2 X_{21} + y_2 Y_{21}}{R_{21}} & \frac{x_3 X_{31} + y_3 Y_{31}}{R_{31}} & \frac{x_4 X_{41} + y_4 Y_{41}}{R_{41}} \\ \frac{-Y_{12}}{R_{12}} & \frac{-Y_{22}}{R_{22}} & \frac{-Y_{32}}{R_{32}} & \frac{-Y_{42}}{R_{42}} \\ \frac{X_{12}}{R_{12}} & \frac{X_{22}}{R_{22}} & \frac{X_{32}}{R_{32}} & \frac{X_{42}}{R_{42}} \\ \frac{x_1 X_{12} + y_1 Y_{12}}{R_{12}} & \frac{x_2 X_{22} + y_2 Y_{22}}{R_{22}} & \frac{x_3 X_{32} + y_3 Y_{32}}{R_{32}} & \frac{x_4 X_{42} + y_4 Y_{42}}{R_{42}} \end{bmatrix} \quad (9)$$

From Eqn.(8), an estimate value of $f(\hat{f})$ can be derived as

$$f = G^+ F \quad (10)$$

where G^+ is the pseudo-inverse matrix of G matrix. From Eqn.(??), the estimated location of the center of friction \hat{p}_g can be obtained as

$$\hat{p}_g = \frac{X^T \hat{f}}{e_n^T \hat{f}} = \frac{X^T G^+ F}{e_n^T G^+ F} \quad (11)$$

where X^T represents the location of each vertices of the rectangle and can be written in matrix form as

$$X = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 \\ y_1 & y_2 & y_3 & y_4 \\ 0 & 0 & 0 & 0 \end{bmatrix}^T \quad (12)$$

where e_n represents unity vector with four elements as

$$e_n = [1, 1, 1, 1]^T \quad (13)$$

D. Pushing Algorithm

In order to push a rectangular micro-object to achieve pure translational motion, it necessary to get the friction distribution and location of the varying center of friction as discussed in above Subsection for online estimation of COF. The pushing operation is performed in several steps as follows:

- Step 1: Aligning the micro-cantilever such that the probe is in contact with the rectangular micro-object at the midpoint of the length using the bilateral teleoperation as discussed in Section IV.
- Step 2: Human operator starts to push the object using bilateral teleoperation and monitors the behavior of the object using visual display. Concurrently, the visual processing starts as discussed in above subsection to generate the position and velocities of vertexes and contact point.
- Step 3: The data from visual processing is utilized to calculate the center of rotation p_r and concurrently the force exerted F_c by the probe is utilized to calculate F_{cx} , F_{cy} and M_{cz} as discussed above.
- Step 4: The matrix F_c and G are formed using two successive visual and force data sets. The force data is downsampled and averaged to 30 Hz to matching the sampling rate of visual frame capturing.
- Step 5: The value of the center of friction p_g is estimated using the values obtained in Step 4 and thereafter desired value of the velocity of the probe in x-direction \vec{V}_x is calculated as discussed in above subsection so that the vector of the resultant can be orientated to ensure that the lone of action passes through the estimated center of friction.
- Step 6: \vec{V}_x is set to the calculated value and kept constant until the arrival of new visual data.
- Step 7: The human operator continuously monitors any sliding of the micro-object at the contact point which may result if the probe comes out of the friction cone. When sliding occurs, the human operator reverts back and changes the location of the contact point after rotation stages is orientated to proper value.
- Step 8: Step 3 is repeated using the next visual data and the first three rows of G matrix are updated each time new data sets becomes available. Step 3 to Step 6 are repeated in a recursive manner to track the location of the center of friction.

Human operator is responsible for generating desired force for pushing of the micro-object by visualizing the motion of the micro-object and can pull the probe back if undesirable behavior in the motion of the micro-object is observed during any of the above mentioned steps. Since humans are very good at adapting to unexpected change in the forces, the force controlled pushing operation is administered by human operator.

E. Experimental Validation of Pushing Operation

In order validate the above mentioned pushing algorithm, several intermediate experiments were conducted by pushing

a rectangular micro-object of size $200\text{ }\mu\text{m}$ at the mid-point of the length of rectangle and the line of action passes through the center of mass. Figure 10 demonstrates the snapshot of the pushing operation and it can be clearly observed that after several steps the micro-object starts to rotate. Thus, it is unmanageable to translate a micro-object by pushing through the center of mass.

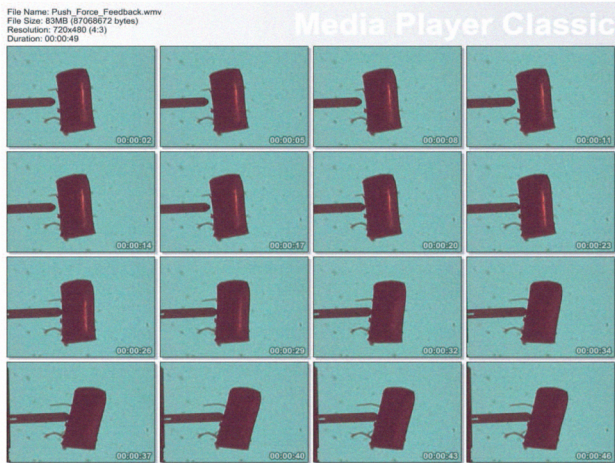


Fig. 10. Snapshot of pushing rectangular object at the mid-point of the rectangle and line of action passes through center of mass of the object.

The above results provides necessary arguments to conclude that to achieve pure translation motion it is necessary that the line of action passes through the center of friction to compensate the orientation angle. Figure 11 demonstrates the snapshot of pushing rectangular micro-object such that the line of action passes through the center of friction. It can be clearly seen that the proposed procedures was able to compensate the orientation effect to attain pure translational motion.

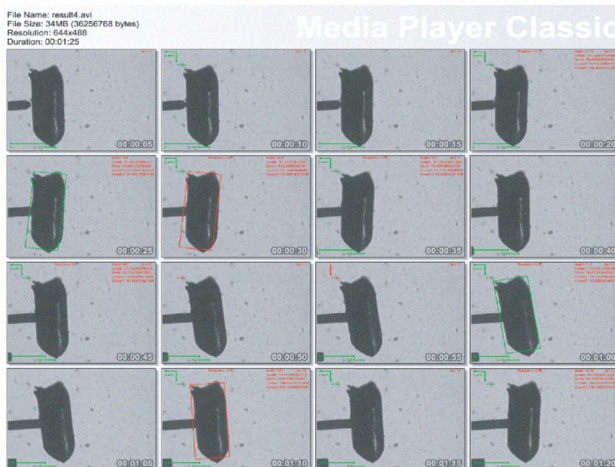


Fig. 11. Snapshot of pushing rectangular object such that the line of action passes through the center of friction

VI. CONCLUSIONS

In this paper, a method for pushing polygonal micro-object in semi-autonomous scheme based on hybrid vision/force

feedback using a custom built tele-micromanipulation is proposed. The goal is to push the micro-object to achieve pure translation motion using semi-autonomous mechanism with the aid of human operator. The pushing operation is undertaken by the human operator using visual display which acts an impedance controller and can switch between velocity control to force control by adjusting the stiffness (muscle stiffness) depending upon the behavior of the motion of the micro-object. Visual module provides the information about the position and orientation of the micro-object to calculate the time-varying COF (center of friction) in recursive manner for each captured frame. The velocity at the contact point is altered using visual feedback procedures such that the resultant direction of velocity passes through the COF to achieve pure translational motion. Experimental results concerning nano-newton resolution force sensing, force/position tracking between the master and the slave is presented which is a requirement to fulfill the pushing operation.

VII. ACKNOWLEDGMENTS

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